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by

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TECHNOLOGY OF THE RADIATION HARDENED MOS DEVICES

M. Dragan, I. Draghici, D. Sachelarie and M. Sachelarie

Abstract

TECHNOLOGY OF THE RADIATION HARDENED MOS DEVICES. 1. Introduction. 2. Technological processes and radiation hardness. 3. Conclusions. The technological conditions necessary for obtaining radiation hardened MOS devices are reviewed. Silicon, silicon dioxide and metallization preparation and subsequent treatments are presented in order to achieve a very low shift in the threshold voltage (up to only 1-2 V) under neutron radiation of a 10^6 rad (Si) total dose.

Introduction

Ionizing radiations create in oxide electron-gap pairs /1-3/. The gap capture cross-section of the oxide traps is greater /4-5/ than that for electrons. The traps are located at a distance of about 150 Å /3,6-8/ of the Si-SiO₂ interface. Under the positive effect of the gate the electron-gap pairs separate, the electrons being collected by the metal door, whereas the gaps are headed towards the interface, where they are trapped as may be seen in Figure 1. Consequently the fixed positive source in oxide /1-3,9/ is the Si-SiO₂ interface, and moreover the number of fast states of the interface increases /10-11/ it seems because of the flow of gas /12/. By this means the MOS devices irradiated under positive polarization undergo a strong displacement of the threshold voltages with negative values. The value of the shift increases with the radiation dose and possibly becomes saturated. In case of zero polarization, the variation of the threshold voltage is theoretically zero, because the electron-gap pairs recombine through a process of "crowding" /13/. In negative polarization the electron-gap pairs separate, but only the gaps created over the length of 150 Å of the interface with silicons are trapped. Therefore the negative shift of the threshold voltages appears, but the value is much smaller than in the

case of positive polarization. The manner in which the threshold voltage varies as a function of the polarization of the gates during irradiation is shown in Figure 2. The rapid states are independent of the polarization of the time of radiation and their number increases along with the dose /6/.

The radiation may appear when using the MOS devices in space, military applications, in the nuclear industry, etc. or during the time of technological processes such as: ion implantation, metalization with electron beams, etching in plasma, lithography with electrons.

The devices implemented with the ordinary MOS technology show shifts of the threshold voltages of tens of volts after a powerful irradiation /14/. Recently through technological optimization we have obtained radiation hardened devices, by this we mean devices with shift of the threshold voltage of at maximum 1 to 2 V, under an irradiation of 10^6 rad (Si).

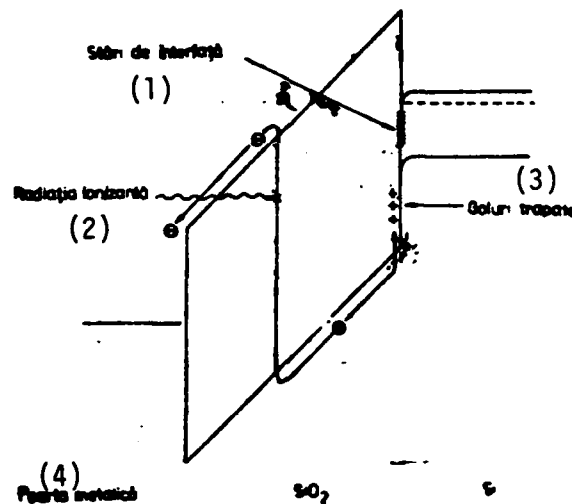


Fig. 1: Diagrams of energy bands of MOS devices irradiated under positive polarizations with gates /8/. Key: (1) interface state; (2) ionizing radiation; (3) gap strapped; (4) metal gate.

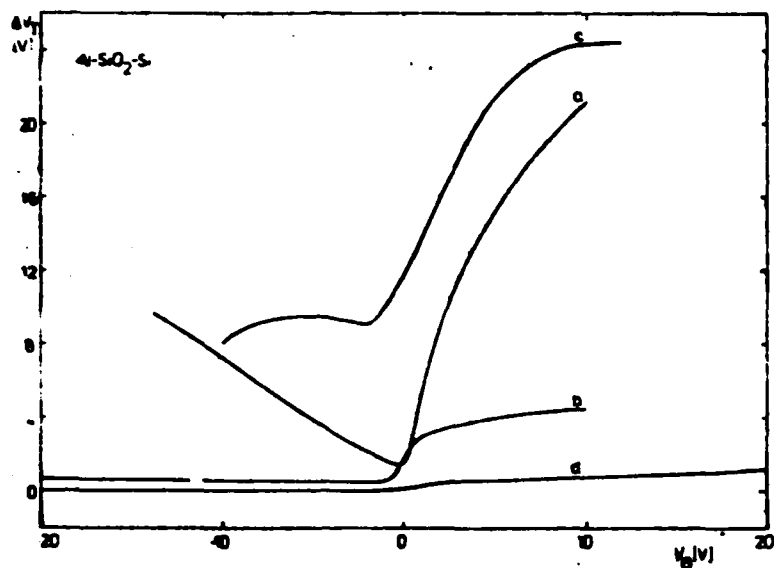


Fig. 2: Shift of the threshold voltage and of the voltage of smooth band as a function of the polarization of the gate during the time of irradiation: a) /39/- ΔV_T at 10^5 rad; b) /19/- ΔV_T at 10^6 rad; c) /54/- ΔV_{FB} at 2.4×10^8 rad; d) /17/- ΔV_{FB} at 3×10^4 rad.

Figure 3 compares the shift of the threshold voltage for the devices obtained by the ordinary technology and by the proved technology, irradiated up to a dose of 10^7 rad.

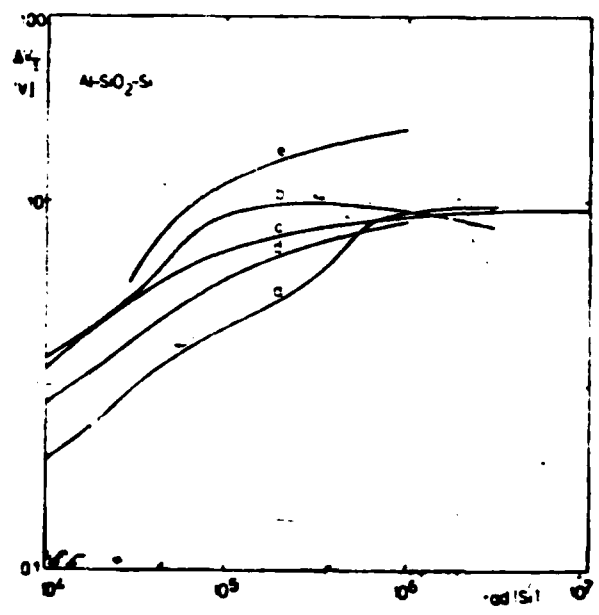


Fig. 3: Shift of the threshold voltage of the radiation dose: a) /41/- $V_G=0V$; b) /41/- $V_G=-10V$; c) /39/- $V_G=0V$; d) /35/- $V_G=0V$; e) /14/- $V_G=0V$.

This article presents the main problems connected with the technology of the radiation hardened MOS devices, reported so far in the specialized literature.

2. Technological Process and Hardening under Radiation

2.1 Silicon

The concentration and type n or p of silicon are of secondary importance /6,15/ as regards the resistance to radiation of the MOS devices. On the orientation plates (100) and (111) a similar behavior is found under irradiation, the charge induced in the oxides being independent of the orientation /2,6/. The silicon of orientation (100) is however less sensitive to radiation /16,17/ mainly because of the smaller number of rapid states of the interface /18,19/.

The surface defects which may appear in different stages of the processing of silicon plates, have an important role /15/, the plates with less than 100 defects/cm² /20/ having a resistance to radiation of over 10⁶ rad. The electric correlation between the number of defects as a resistance to radiation may be obtained by the measurement of the transit time of the mobile charge carriers of the silicon surface. A transit time of more than 40 μs /21/ assures the resistance to a dose of 10⁶ rads. The initial quality of the surface may be improved by etching in HCl before oxidation /21,22/. The increase of the transit time to values above 100 μs may be achieved by the technique of freezing of the back of the plates, using: P₂O₅, Si₃N₄; ionic implantation, POGO technique (freezing by preoxidation of the substrate). This treatment requires the application beforehand of any technological process with increased temperature /21/.

2.2 Thermal Oxidation

a. Type of Oxidation

Dry oxidation seems to assure the best resistance to radiation /8,16,19/. Since the charge induced by radiation depends probably on the presence of mobile ions of sodium of the oxide /8,16/, Hughes /23/ recommends the introduction in the oxidation atmosphere of hydrochloric acid in a percentage of 1 to 10 percent; the

role of HCl is to capture the sodium atoms from the structures and to introduce chlorine in the oxide which reduces the mobility of the sodium ions. It was observed more recently /24/ that the presence of chlorine increases the sensitivity to radiation and that the threshold voltage in case of irradiation under positive polarization of the gate is proportional to the percentage of HCl in the oxidation atmosphere. This is therefore advisable since the use of hydrochloric acid also limits the purging of the furnace before oxidation.

The disadvantage of the oxidation under vapors is that it cannot assure the proper value of the initial special value, while the reproducibility is also lower, because it is a process which is less controllable. The resistance to radiation is lower /19/ as compared with that given by the usual oxidation, contrary to the results obtained from older investigations /2,25/. It may be improved by adding HCl or H₂ in oxidizing atmosphere. For oxide thicknesses more than 1,000 Å the pyrogenic oxidation is superior to ordinary oxidation /26/.

The humid oxidation may be used if it is followed by a short-term ordinary oxidation /19/.

Independently of the type of oxidation, hardening under radiation requires the optimization of the oxidation temperature and the treatment for stabilizing the oxide /8,15,16,19,27/.

It is absolutely necessary that whatever the type of oxidation used, the medium in which the process takes place should not contain alkaline products. The oxidation tube must be well-rinsed with HCl before oxidation /8,20,23,24,27/.

The different methods of rinsing the plates before oxidation do not assure the hardening under radiation of the devices /15,28/. The cleaning of the plates in sulfuric acid, followed by the rinsing in hydrofluoric acid is sufficient. Likewise the application of different types of photoresistors on oxide does not modify the sensitivity to radiation /15,28/.

b. Thickness of the Oxide

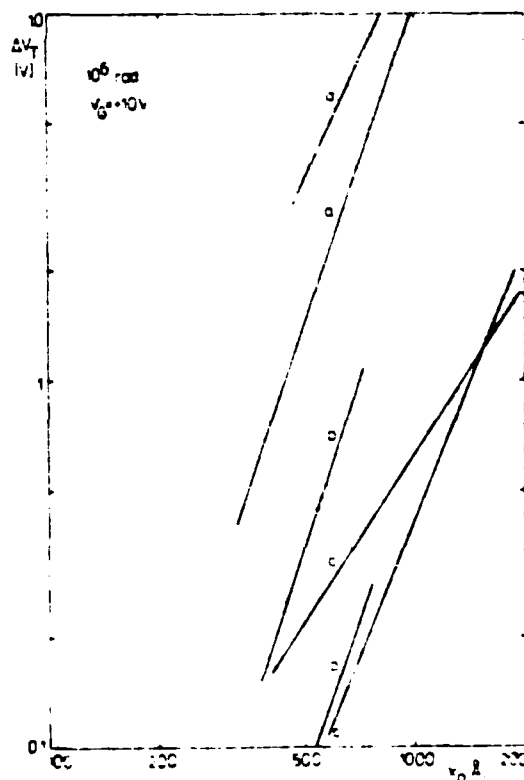
The resistance to radiation depends to a great extent on the thickness of the oxide, the best results are obtained with thin oxides /15,22,25,27-32/. The dependence of the maximum variation of the threshold voltage ΔV_T of the thickness of the oxide X_{Ox} follows the law

$$\Delta V_T = kX_{Ox}^n$$

If experimental value found for n differs from one author to another as a function of the radiation energy and the conditions of oxidation.

In case of irradiation with ^{60}Co (gamma rays) and dry oxidation /15,28,30/ $n=3$ is obtained. Likewise the value $n=2$ was reported /15,30/ if the initial oxide grew over the entire plate to a same thickness, at the same time and afterwards etched to different dimensions. Hughes /32/, using 1 MeV electron radiations obtained $n=2$; using ultraviolet light (10.2 ev) obtained $n=1$. By oxidation under vapors and irradiation with 1 MeV electrons, Schlesier /27/ gave $n=2$.

Fig. 4: Shift of the threshold voltages as a function of the thickness of the oxide for MOS devices irradiated with 10^6 rad (Si) under conditions $V_G = +10V$: a)/28/, b)/30/, c)/26/.



This spread of values obtained experimentally illustrated in Fig. 4 may be explained by an intuitive model, according to the following: The shift of the threshold voltages is

$$\Delta V_T = \frac{Q}{C_{Ox}} = x Q X_{Ox};$$

where Q is the total net charge of the gaps trapped in oxide following the process of generation of electron-gap pairs by irradiation.

The traps seem to be located only in the Si-SiO₂ interface, over an average distance of approximately 150 Å. The number of electron-gap pairs created by ionization is the same at any point on the oxide.

If the number of traps N_T does not depend on the conditions of oxidation and the ionization takes place only on the surface of the oxide (low energy) then Q does not depend on the thickness of the oxide and $\Delta V_T \sim X_{Ox}$. In situations in which the ionization is uniform over the entire thickness of the oxide (high energies), $Q \sim X_{Ox}$ and $\Delta V_T \sim X_{Ox}^2$. If N_T depends on the conditions of oxidation, therefore are correlated with the thickness of the oxide /31/, the result is $\Delta V_T \sim X_{Ox}^2$ and $\Delta V_T \sim X_{Ox}^3$ according to whether the energy of the ionizing radiation is small or large respectively.

c. Temperature of Oxidation

For a certain type of oxidation there is an optimum temperature which assures the maximum resistance in the radiation field. This temperature value is: 1,000 °C for the dry oxidation /8,15,16,19,23,28,33-35/, in the area of 900 °C for the oxidation in vapors with HCl in the oxidation atmosphere /8,27/ and 850 to 925 °C for pyrogenic oxidation under vapors /8/ as may be seen in Fig. 5.

The lower temperatures require a longer time of oxidation, altering the dielectric quality of the oxide. At higher temperatures than the optimum one, the oxidation times are too short for an adequate control of the process and moreover the regions diffused beforehand undergo excessive diffusion /19/.

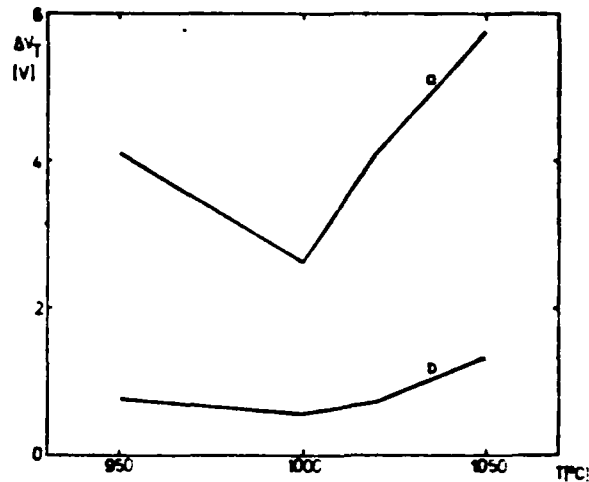


Fig. 5: Shift of the threshold voltages as a function of the temperature of oxidation for MOS devices irradiated with 10^6 rad (Si)/28/: a) $-V_G = +10V$; b) $-V_G = -10V$.

The speed of oxidation seems to be important also. At a constant temperature, a different speed of increase of the oxide is obtained by variation of the partial oxygen pressure [15,28]. If the value of the partial pressure is controlled by using argon as carrier gas, the resistance to radiation does not depend on the speed of oxidation. Nitrogen is used, the increase of the speed of oxidation causes a drastic degradation of the shift of the threshold voltage. This may be explained by the fact that part of the nitrogen is incorporated in the Si-SiO₂ interface, increasing by this means the number of tracks.

d. Heat Treatment for Stabilization

The stabilization treatments in nitrogen or argon are needed normally after oxidation at relatively low temperatures (1,000°C) to reduce the values of the threshold voltages [36]. It was also observed that the stabilization treatments of the oxide conducted at higher temperatures than 925°C reduces the resistance to radiation even for short periods of stabilization [15,17,19,22]. For this reason it is necessary to achieve a compromise between a sufficiently low temperature so as not to reduce the resistance to radiation and a stabilization time which must be long enough to reduce the initial value of the threshold voltage.

At all temperatures of stabilization the sensitivity to radiation increases together with the increase of the time above a certain value, according to the law $\Delta V_T \sim T^2$ /27/. For each temperature there is an optimum time: of the order of tens of minutes under 950°C and less than a minute above this temperature. After the dry oxidation, the optimum stabilization treatment is at 800 to 850°C, 90 minutes /8,15,19/. For oxidation in vapors the optimum treatment is 875 to 925°C, about 10 minutes /8,19,27/. The inert medium, nitrogen or argon, in which the stabilization is accomplished does not seem to be very important /15/.

e. Passivation Treatment

Hardening under radiation is obtained by depositing on the oxide a layer of phosphorus glass /25,37/. The passivation treatment of the layer of SiO₂ with P₂O₅ was studied previously with a view to reducing the instabilities caused by sodium ions. Phosphorus glass acts as a freezing agent and reduces the effective concentration of impurities in the oxide layer. The improvement of the resistance to radiation by depositing phosphorus glass has been described /34,38/ for the case of positive polarization of the gate. More recently /39/ devices passivated with P₂O₅ have been obtained with high resistance to radiation, both for positive and negative polarization of the gate.

The other passivation was obtained by using silicon nitrides /6/. Si₃N₄ deposited on a thin oxide leads to the production of an MOS device with a satisfactory behavior in a radiation field /34,37,40/. The explanation is that a dielectric layer with greater relative conductance will have a lower charge induced by radiation and moreover will create a new Si₃N₄-SiO₂ interface modifying in a favorable direction the trapping process.

After depositing layers of Si₃N₄ or P₂O₅ as passivating agent heat treatments of stabilization at higher temperatures are needed.

2.3 Metallization

a. Type of Metal

The use of metallization with chromium causes a decrease of the sensitivity to radiation of the MOS devices /35,38,41-44/. The comparisons of the behavior of devices with undergoing metallization with chromium and aluminum (metallization with electron beam) reveals the advantage of the use of chromium. The initial speed of shift of the threshold decreases by one order of magnitude and the maximum shift of the threshold decreases two or three times; a lower energy is needed for the evaporation of this metal thickness, chromium assures a greater protection for the oxide of the gates, since $Z=24$ (for aluminum $Z=13$); the multivalent nature of chromium causes a chemical stability of the large range of impurities. Fig. 6 shows comparatively the variation of the threshold voltage with dose for devices undergoing metallization with chromium and aluminum.

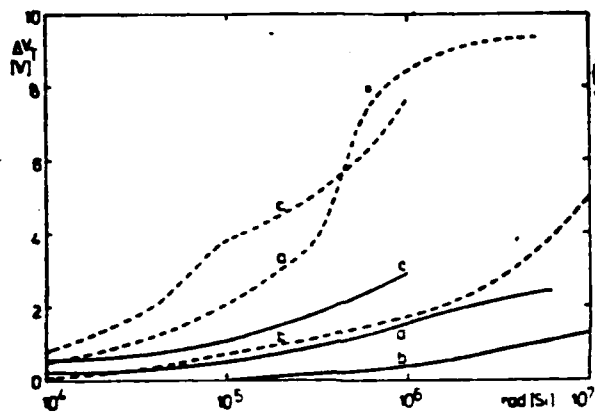


Fig. 6: Shift of the threshold voltage for devices with Al gate (dashed line curves) and Cr (solid curve) in conditions $V_G=0$: a) /41/; b) /38/; c) /35/.

The metallization with chromium also presents drawbacks: the state density of the interface is dependent to a great extent on the condition of polarization of the period of irradiation; to eliminate the irradiation effect a treatment at a higher temperature than the one for aluminum is needed; the preparation of the oxide assumes greater importance.

The use of aluminum leads to a good behavior of the MOS devices in a radiation field if it is deposited by heating a filament /19/ and not by bombardment with electrons. If a chromium layer is deposited on the oxide, then an aluminum layer, both by heating of a resistance, a certain improvement is obtained in the behavior

of the irradiated MOS devices, thanks to the inhibition of the formation of rapid states /24/ especially at zero or positive gate voltages.

The dependence of the thickness of the metal of the gate was studied by Zininger /2/ who observed the decrease of the sensitivity to radiation for thin gates (0.1 μm) and the saturation to sensitivity for thick gates.

b. Method of Deposit

The metal deposits carried out by the method of bombardment with electrons is carried out in the presence of low energy Z-rays, which creates defects in the region of the surface of the oxide. This process decreases the resistance to radiation of the devices polarized negatively on the gate, but have a lower effect for those polarized positively /15/. A second effect is the trapping of gaps created by irradiation with X-rays in the centers of the Si-SiO₂ interface. Therefore an additional shift appears in the special voltages, but it may be eliminated by the sintering treatment of metal. Metallization with an electron beam is advantageous as it prevents the contamination of the device during the deposit /35/.

The deposits achieved by evaporation of the metal by means of a heated filament are far superior because they prevent the appearance of X-rays. This is important as the source of deposit should have a low content of alkalines /8/.

c. Sintering

In principle the sintering treatment assures the ohmic contact of the metal with silicon and the decrease of the fixed charge of the oxide. The increase of the resistance to radiation is obtained for higher sintering treatment /15,19,35/. A too high value of the sintering temperature decreases however the yield of the production by the increase of the occurrence of short circuits of the gate. The optimum temperatures are 460 C (15 to 30 minutes) for chromium /35/ and 500°C (15 minutes) for aluminum /19,22/35/.

From the viewpoint of the resistance to radiation, sintering in nitrogen seems to be superior to sintering in other gases. The incorporation of hydrogen in oxides during the sintering treatment has an adverse effect to the resistance to radiation /15,22/.

In the sintered devices the curve C-V after radiation are more distorted than for nonsintered devices. This may be due to the nonuniform trap or to the additional increase to the rapid states /27/.

In manufacturing the radiation hardened MOS devices sintering has the additional role of eliminating defects induced by the metallization with electron beams and of favoring the diffusion of metal in the oxide /19,35,42,43/.

2.4 Ion Implantation

Recently in the technology of MOS devices, the technique of ion implantation has been used increasingly, replacing the diffusion processes. During this treatment the oxide undergoes considerable degradation because of the displacement of atoms of the lattice, primary and secondary ionizations. A considerable portion of the atoms implanted in silicon occupy interstitial positions and to be activated a heat treatment with tempering is needed, which takes place at temperatures higher than 800°C /45/. This treatment eliminates at the same time the fixed charge of the oxide induced by irradiation during the time of implantation, while the temperature of 500°C is needed for stabilization. The defects introduced by implantation in oxide (neutral traps) are stabilized between 600 and 700°C /46/, the tempering treatment of the atoms implanted in silicon are therefore covered also under this aspect.

Another solution may be the removal of the oxide immediately after implantation and the increase of new oxide during the tempering treatment.

In case implantation takes place on the deposit of the metal gates, it is recommended that its thickness be greater so as not to permit the penetration of ions in the oxide from under the gate /19/.

In general the effect of the implantation of the oxide may be optimized by reducing to the minimum the dose and the masses of the atoms implanted and by increasing the temperature and time of tempering /47/.

All these problems appear therefore after a process of implantation of silicon atoms. But the implantation may be used as a process in the sense of increasing the

resistance to radiation of the thermal oxide. For this purpose atoms of Al, Cr, Ar, B, Ce, Xe, He are implanted /17,24,33,34,48-52/ in oxide, since they increase the speed of the trapping of the electrons generated in oxide, providing therefore the balance to the gap trapping processes. But the sensitivity to radiation depends on the polarization of the gate and the concentration and energy of the ions implanted. Thus for Al^+ which is the one most mentioned, the sensitivity to negative polarization increases or is equal to that of the oxides without implantation, whereas for positive polarization the sensitivity decreases with the increase of a concentration of implanted atoms, becoming zero at a given concentration. Above this value the shift of the threshold voltages after irradiation becomes positive, indicating a net negative charge in the oxide (predomination of the electron trapping processes) /34,49,52/. To eliminate the excess positive charges after implantation a treatment at higher temperature is needed; the sintering process of the aluminum gate which takes place at $500^\circ C$ is sufficient /24,49/. It is absolutely necessary that this process should take place in a highly clean oven (purged with HCl) because the Al^+ ions represent a very powerful freezer for sodium /24/.

Good results are obtained by implanting atoms of chromium in oxide /33/.

2.5 Other Technological Processes

Etching in plasma is used for outlining the polysilicon gate which is under a layer of thermal oxide. During the time of the process itself the oxide is exposed to a bombardment with positive ions, electrons, X-rays, ultraviolet light, leading to the appearance of fixed positive charges and rapid states of the interface. The shift of the threshold voltages may be eliminated by a heat treatment carried out after metallization or by reducing the acceleration voltage /47/.

Optical lithography may be used in devices of small dimensions, being replaced by lithography with electron beams (or lithography with X-rays). In such a process the typical energy of acceleration is 25 keV, sufficient for producing ionization in oxides. The charge introduced in irradiation is eliminated by a sintering treatment of the metal /47,53/. The decrease of the dose is not implemented since it implies the improvement of the sensitivity to resistance to an electron beam /47/.

3. Conclusions

The gaps generated by irradiation in oxide are trapped in the actual Si-SiO₂ interface, producing a shift with negative values of the threshold voltage of the irradiated MOS devices. The shift may be reduced substantially (at maximum 1-2V at 10⁶ rad) by optimizing the technological processes. The analysis of the data described in the literature makes it possible to draw the following conclusions with regard to the production technology of the radiation hardened MOS devices:

1. Silicon has to be of orientation (100) with a transit time greater than 100 μ s.
2. The oxidation tube must be washed in an HCl solution.
3. The thickness of the oxides must be as small as possible.
4. For each type of oxidation there is an optimum temperature: 1000°C for dry oxidation and 850-925°C for oxidation under vapors.
5. There is an optimum treatment for stabilization of the oxide: 850°C, 90 minutes for dry oxidation and 875-925°C, 10 minutes for oxidation under vapors.
6. The deposit of metals must be accomplished with evaporation with a heated filament from a source with a low content of alkaline substances.
7. There is an optimum sintering treatment: 460°C, 15-30 minutes for chromium and 500°C, 15 minutes for aluminum.
8. The implantation of aluminum or chromium ions in silicon oxide is useful.
9. The effect of irradiation introduced by technological processes may be eliminated by the process of thermal stabilization.

The other technological problems seem to be of secondary importance in the production of radiation hardened MOS devices.

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